

Neutron Star Binaries as Central Engines of GRBs

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Abstract. We describe the results high resolution, hydrodynamic calculations of neutron star mergers. The model makes use of a new, nuclear equation of state, accounts for multi-flavour neutrino emission and solves the equations of hydrodynamics using the smoothed particle hydrodynamics method with more than 10^6 particles. The merger leaves behind a strongly differentially rotating central object of $\sim 2.5 M_{\odot}$ together with a distribution of hot debris material. For the most realistic case of initial neutron star spins, no sign of a collapse to a black hole can be seen. We argue that the differential rotation stabilizes the central object for $\sim 10^2$ s and leads to superstrong magnetic fields. We find the neutrino emission from the hot debris around the freshly-formed, supermassive neutron star to be substantially lower than predicted previously. Therefore the annihilation of neutrino anti-neutrino pairs will have difficulties to power very energetic bursts ($\gg 10^{49}$ erg).

INTRODUCTION

There is growing observational evidence that the subclass of long Gamma Ray Bursts (GRBs) is related to star forming regions (e.g. [4]). While this connection is immediately evident for the short-lived progenitors of collapsars, the question of whether neutron star binaries merge close to star forming regions or not is not a settled one. Bloom et al. (2002), for example, argue against compact object mergers as central engines of (at least the subclass of the long) GRBs. Belczynski et al. (2001), however, claim to have identified new formation channels that lead to classes of very tight, short-lived neutron star binaries. They find typical inspiral times of the order 10^6 years and therefore neutron star binaries would merge very close to their birth places, even if equipped with high systemic velocities due to kicks in asymmetric supernova explosions.

Recent afterglow observations of long bursts suggest that they are beamed and require $E_{\gamma} \sim 5 \cdot 10^{50}$ erg [8]. The energy requirements for the subclass of short bursts are so far essentially unconstrained. Due to their gravitational binding energy of several times 10^{53} erg, neutron star binaries certainly do possess the energy reservoirs necessary to power a (long) burst, however, how to transform the available energy into gamma rays is still far from being clear. Among the suggested mechanisms are magnetic energy extraction processes (e.g. [6, 11, 22]) and the annihilation of neutrino-antineutrino pairs emitted from the hot neutron star debris during the coalescence [7].

HIGH RESOLUTION SIMULATIONS OF THE MERGER EVENT

To study the possible role of neutron star coalescences for either long or short bursts we have performed detailed high-resolution simulations of the merger event [15]. To solve the equations of fluid dynamics we apply the smoothed particle hydrodynamics method (SPH) together with a largely improved artificial viscosity tensor [14]. We treat the self-gravity of the neutron star fluid in a Newtonian way, but we add the forces emerging from the emission of gravitational waves to drive the system towards coalescence. The microphysical properties of the hot and dense neutron star matter are described using an equation of state (EOS) that is based on the tables of Shen et al. [19, 20]. We have extended the EOS to the low density regime via a gas consisting of neutrons, protons, alpha particles, electron-positron pairs and photons. This new EOS covers the whole relevant parameter space in density, temperature and electron fraction. To allow for cooling and compositional changes, we have implemented a detailed neutrino treatment that accounts for three neutrino flavours ($\nu_e, \bar{\nu}_e$, and ν_x , which is collectively used for the four heavy-lepton neutrinos) and takes the relevant emission processes (lepton capture on nucleons, electron-positron pair annihilation and plasmon decay) into account. The opacities are calculated from the absorption processes of the electron-type neutrinos on nucleons and scattering off nucleons and nuclei, the latter process becoming the dominant opacity source even for moderate mass fractions of heavy nuclei. The calculations are performed efficiently on shared-memory

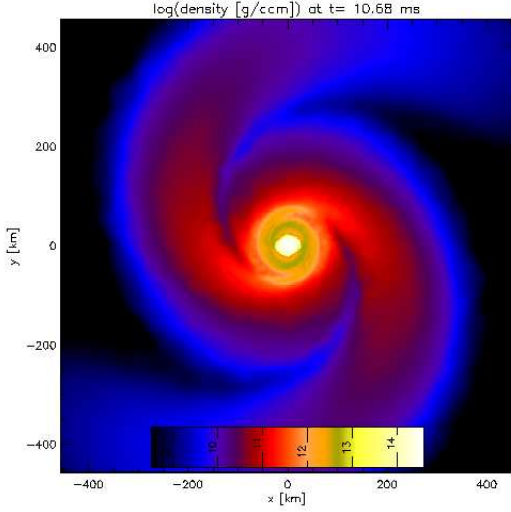


FIGURE 1. Coalescence of a corotating binary system of $1.4 M_{\odot}$ per star. Colour-coded is the matter density in the orbital plane. More than 10^6 SPH-particles were used for this calculation.

parallel computers with more than 10^6 SPH-particles. For a more detailed description of the input physics and the computational methods we refer to Rosswog et al. [15, 16].

RESULTS

In this latest set of calculations we explore systems with two initial spin configurations (for details see [15]): tidally locked, corotating systems for the ease of constructing initial equilibrium models and systems without initial neutron star spins. The latter ones are the most relevant spin configurations since the intrinsic neutron star viscosity is too low to lead to a tidal locking during the short phase where the binary components undergo tidal interaction [3, 10]. We find central objects of 2.3 to $2.6 M_{\odot}$ which are strongly differentially rotating. For the most realistic, irrotational case the maximum density does not even reach the initial density of a single, cold non-rotating neutron star. Apart from the thermal pressure and the differential rotation there may be further effects that, at least temporarily, stabilize the merger remnant against collapse to a black hole: the presence of non-leptonic, negative charges together with trapped neutrinos [13], for example, can substantially increase the maximum possible mass. One also expects magnetic seed fields to be amplified in the differentially rotating remnant to enormous field strengths ($\sim 10^{17}$ G) [6]. Fields of this strength can substantially modify the structure of the central object and provide additional support

against collapse [5]. Due to our ignorance of the high-density equation of state it cannot be ruled out that the end product of the coalescence is a stable supermassive neutron star of $\sim 2.8 M_{\odot}$. It seems, however, more likely that the central object is only temporarily stabilized and once the stabilizing effects weaken (e.g. neutrinos have diffused out after ~ 10 s, magnetic braking has damped out differential rotation) collapse to a black hole will set in. The time scale until collapse is difficult to determine, since it depends sensitively on poorly known physics and on the specific system parameters. We expect the most important effect to come from the differential rotation [12, 1] and therefore the collapse time scale to be set by the time it takes the remnant to reach uniform rotation. Assuming the dominant effect to come from magnetic dipole radiation (the viscous time scale is estimated to be $\sim 10^9$ s [18]), this time is given by

$$\begin{aligned} \tau_c &\sim \frac{18c^3 M}{5B^2 R^4 \omega^2} \\ &\sim 10^2 s \left(\frac{M}{2.5 M_{\odot}} \right) \left(\frac{10^{16} \text{G}}{B} \right)^2 \left(\frac{15 \text{km}}{R} \right)^4 \left(\frac{3000 \text{s}^{-1}}{\omega} \right)^2, \end{aligned}$$

where M, B and R are mass, magnetic field and radius of the central object. Such an object, an at least temporarily stabilized, supermassive neutron star with enormous magnetic field strength, is at the heart of many suggested GRB models (e.g. [6, 22, 9]). Kluzniak and Ruderman, for example, estimate that the magnetic field becomes buoyant at $\sim 10^{17}$ G, floats up and breaks through the surface of the remnant as a sub-burst. This process, winding up the field to buoyancy, subsequent floating up and sub-burst, would continue until the energy stored in differential rotation is used up (or collapse sets in), ~ 100 s. Therefore even long bursts, with substructures on millisecond time scale set by the motion of the magnetized fluid, could result from a neutron star merger. Once the differential rotation has been damped out, the system could still continue as a gamma ray burster using the energy stored in rigid rotation [21] in case it remains stable, or, in case of collapse, one would be left with the 'classic' GRB-engine, a black hole plus a debris torus.

The annihilation of neutrino anti-neutrino pairs into electron-positron pairs above the poles of the merger remnant has been suggested [7] as a process to produce a fireball from thermal energy stored in the disk. We find that the main neutrino-emitting region is the inner, shock- and shear-heated region of the torus around the central object. The prevailing densities lie between 10^{10} and $10^{12} \text{ g cm}^{-3}$ and temperatures are ~ 2 - 3 MeV. In our simulations we find typical neutrino luminosities of $\sim 10^{53}$ ergs with mean energies of $\sim 10, \sim 15$ and ~ 20 MeV (see Fig. 2) for an initially corotating system, and slightly higher values for irrotational systems [16]. The dominant emission process is the capture of positrons

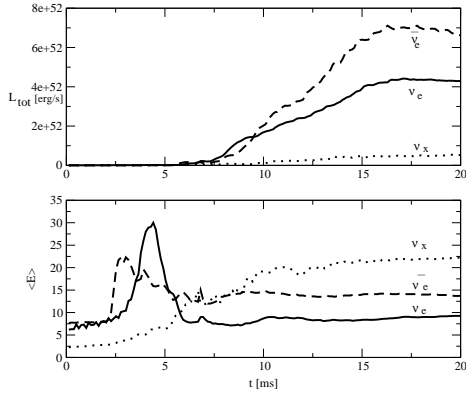


FIGURE 2. Total neutrino luminosities and mean energies (in MeV) for the ν_e , $\bar{\nu}_e$ and ν_x emitted in the coalescence of a corotating neutron star binary system of twice $1.4 M_\odot$. The abscissa gives the time in ms.

onto neutrons which occurs in the hot, neutron-rich inner regions of the debris torus. The found luminosities are lower than those found previously by Ruffert and Janka [17] by roughly a factor of 3 to 4. The annihilation efficiency is currently being investigated in detail, but the preliminary results indicate that it will be difficult to power Gamma Ray Bursts largely in excess of $\sim 10^{49}$ ergs.

SUMMARY

We have performed high resolution calculations of neutron star coalescences with more than 10^6 SPH-particles, using a new, nuclear equation of state and accounting for the effects of cooling and compositional changes from neutrino reactions by a detailed multi-flavour neutrino treatment. For the most realistic case with negligible neutron star spins, we do not see any sign of a collapse to a black hole and therefore argue that the outcome of the coalescence is a (at least temporarily) stabilized, supermassive, hot, differentially rotating object with huge magnetic fields. Such an object could produce a GRB in various ways, e.g. via a relativistic electron-positron wind (Usov 1994) or via the so-called DROCO-mechanism (differentially rotating compact object) suggested by Kluzniak and Ruderman (1998) where the field inside the differentially rotating central object becomes locally wound up until it becomes buoyant at $\sim 10^{17}$ G, floats up and breaks through the surface as a sub-burst. This self-limited process would continue until the differential rotational energy is used up and would therefore continue for several seconds with substructures given by the fluid instabilities on a millisecond time scale.

We have further analyzed the neutrino signal expected from the event. The neutrino emission is dominated by anti-neutrinos produced in positron captures, the total luminosities lie around $\sim 10^{53}$ erg/s and are substantially lower than those found in previous investigations. Preliminary analysis of the neutrino anti-neutrino pair annihilation efficiency suggests that it is difficult to power energetic bursts with energies $\gg 10^{49}$ ergs via this mechanism. Whether this energy is enough to power a short GRB will have to be clarified by future afterglow observations.

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REFERENCES

1. Baumgarte T., Shapiro S., Shibata M., 2000, ApJ, 528, L29
2. Belczynski, K., Bulik, T. and Rudak, B., astro-ph/0112122(2001)
3. Bildsten, L. and Cutler, C., ApJ, 400, 175 (1992)
4. Bloom, J.S, Kulkarni, S.R. and Djorgoski, S.G., AJ, 123, 1111 (2002)
5. Cardall, C. et al. ApJ, 554, 322 (2001)
6. Duncan, R. and Thompson, C., ApJ, 392, L9 (1992)
7. Eichler, D. et al., Nature, 340, 126 (1989)
8. Frail, D. et al., ApJ, 562, L55 (2001)
9. Kluzniak, W. and Ruderman, M., ApJ, 505, L113 (1998)
10. Kochanek, C.S., ApJ, 398, 234 (1992)
11. Narayan, R., Paczynski, B. and Piran, T., ApJ, 395, L83 (1992)
12. Ostriker J., Bodenheimer P., 1968, ApJ, 151, 1089
13. Prakash, M. et al., Phys. Rev D52, 661 (1995)
14. Rosswog, S., Davies, M.B., Thielemann, F.-K. and Piran, T., A&A 360, 171 (2000)
15. Rosswog, S. and Davies, M.B., MNRAS in press (2002)
16. Rosswog, S. et al., in preparation (2002)
17. Ruffert, M. and Janka, T., A&A, 380, 544 (2001)
18. Shapiro, S.L., ApJ, 544, 397 (2000)
19. Shen, H. et al., Nucl. Phys. A637, 435 (1998)
20. Shen, H. et al., Prog. Theor. Phys. 100, 1013 (1998)
21. Usov, V.V., Nature, 357, 472 (1992)
22. Usov, V.V., MNRAS, 267, 1035 (1994)